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FINAL

NANOSECOND PULSE BREAKDOWN INITIATION AND GROWTH

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ABSTRACT

The statistics of gaseous breakdown initiation are analyzed in detail. The probability of immediate breakdown is discussed in terms of the lifetime of electron bursts and the frequency of burst generation by cosmic rays and natural radioactivity. The probability of breakdown during the application of the pulse is discussed in terms of field-assisted electron generation at the walls or electrodes of the test cell. The feasibility of photometric techniques in the study of discharge temporal and spatial growth is considered.

PUBLICATION REVIEW

This report has been reviewed and is approved. For further technical information on this project, contact Mr. W. C. Quinn (EMATP) x75141.

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Evaluation of Final Report
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1. The work reported herein is part of a short pulse-range resolution program which has been underway at RADC since 1960. For the most part, interest has been confined to range resolutions of a few feet and pulse energies suitable for long range radar operation, i.e., pulse durations less than twenty nanoseconds and peak power of the order of 10^{10} to 10^{12} watts. Needless to say, microsecond pulse techniques fall far short of solving most of the problems; new technical approaches are needed in most cases.

2. To date, emphasis has been placed on two major problems - generation and breakdown. This contract is mainly concerned with the statistics of discharge initiation and photometric diagnostic techniques; other studies presently underway are investigating discharge growth.* Probably the most important conclusion to come out of this contract is that the probability of breakdown initiation in a nanosecond radar may be quite small. This leads one to speculate on the possibility of a radar in which peak power is well above the limits imposed by discharge growth considerations, and in which a reasonable percentage of the pulses are sacrificed to breakdown. Further study of the latter concept and the photometric diagnostics is contemplated.

*Contract AF30(602)-2779, "Nanosecond Pulse Breakdown Study" with Space Sciences, Inc., Waltham, Mass; theoretical and experimental investigation involving discharge growth in video pulses.

Contract AF30(602)-2782, "Nanosecond Pulse Breakdown Study" with Microwave Associates, Burlington, Mass.; theoretical and experimental investigation involving discharge growth at microwave frequencies.

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30 December 1963

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INTRODUCTION

Gaseous breakdown is a phenomenon which can limit the performance capability of microwave systems operating at high-power levels. It may occur in portions of the transmitter plumbing, at the transmitting antenna, or possibly in regions of free space where local conditions and microwave power concentration obtain.

In the BDM report[1] presenting results of the first six months of theoretical study, it was pointed out that the investigation of discharge-initiating processes has generally been ignored in microwave breakdown studies. It appears, however, that an understanding of these problems may lead to techniques to inhibit initiation and greatly increase the probability of transmitting super power pulses without breakdown. It was also pointed out that photometric measurements of the discharge growth would provide a more sensitive measure of free electron concentration in the breakdown region and give more detailed information about the spatial and temporal growth of the discharge. During the six-month period covered in this report, more detailed investigations have been conducted in these areas; and the results of these investigations are presented in this report.

I. DISCHARGE INITIATION

A. General

There is a time delay between the application of a microwave pulse or a DC voltage pulse to a test volume of gas and the buildup of the discharge in the gas. This time delay is divided into two parts, an initiatory time, t_s, and a formative time, t_f. The initiatory time is the time delay experienced before a discharge-initiating electron appears. It is statistical in nature and, accordingly, is called the statistical time lag. The second part of the total time delay observed in discharge studies is the formative time lag, t_f, which is the time required for the discharge to grow from initiation to levels at which microwave energy is reflected. This growth or formative time is nearly deterministic in nature. Taking these definitions of statistical time lag and formative time lag, the total time lag, t_T, may be expressed as follows:

$$t_T = t_s + t_f \tag{1}$$

Previous studies of microwave discharges have dealt almost exclusively with the formative time, t_f, and the details of discharge growth. The results of these studies appear to establish well-defined limits on the power capabilities of microwave systems. In these studies, however, little or no consideration has been given to the characteristics of the statistical time lag and underlying physical processes. In most cases the statistical time lag is regarded as an experimental inconvenience which is reduced by using artificial radiation to provide an abundance

of discharge-initiating electrons. In examining the discharge phenomenon from the point of view of the transmission of super-power microwave pulses, it is particularly pertinent to study in detail the discharge initiation processes.

For both the microwave and DC cases the appearance of a discharge-initiating electron has similar statistical characteristics and the same underlying physical processes. The time lag depends on the probability that an electron will be liberated in the test gap and on the probability that this electron will initiate an electron avalanche. All processes liberating discharge-initiating electrons are random. They are amenable to the same statistical analysis. Therefore, these statistics will be discussed first. Details of the physical processes producing free electrons will then be discussed.

B. The Statistics of Discharge Initiation

When a voltage in excess of the static breakdown voltage is applied to a test gap, a discharge will not take place until an electron appears in the gap which generates an electron avalanche. As previously defined, the time interval between the application of the voltage to the gap and the appearance of the electron which initiates an electron avalanche is the statistical time lag.

The statistical treatment of the time lag is straightforward. Assume that a large number of trials, n_o, are conducted in which a step function voltage pulse in excess of the static breakdown voltage is applied to a test gap. If time measurements are begun at the time of the application of the voltage pulses, a number, n, will not have

experienced breakdown after an interval of time, t. Then the number, dn, which experience breakdown in the following small interval of time, dt, is given by,

$$dn = -IWndt \tag{2}$$

where I is the average number of electrons which appear per second in the gap and W is the probability that an electron appearing in the gap will lead to a discharge. The negative sign used in the expression indicates that the number of surviving voltage pulses is reduced by dn during the interval of time, t to t + dt. If this expression is integrated, it leads to the expression for n as a function of t as follows:

$$n = n_o e^{-IWt} \tag{3}$$

It is more usual to use the expression for the probability that in a simple measurement the time lag will be greater than a time, t. This is given by the ratio of n/n_o as follows:

$$\frac{n}{n_o} = e^{-IWt} \tag{4}$$

For cases where pulses of width τ rather than step function voltages are applied to the test gap, the probability that breakdown will occur during the time the pulse is applied is given by,

$$P_\tau = 1 - e^{-IW\tau} \tag{5}$$

For the case under consideration here the field applied to the gap will be much greater than the minimum breakdown field. For this case $W \cong 1^2$ and we may write

$$P_\tau = 1 - e^{-I\tau} \tag{6}$$

Equation (6) does not include the probability that there will be an electron or electrons present in the test gap at $t = 0$, i.e., when the pulse is applied. If there is at least one electron present in the gap which leads to an electron avalanche when the pulse is applied, breakdown then occurs immediately. There is a probability that such an electron will be present; therefore, to express the total probability, P_T, that breakdown will occur at the beginning of a pulse of width τ or during the pulse, the probability, P_i, of such an electron being present in the gap must be combined with P_τ, yielding*

$$P_T = P_i + P_\tau \tag{7}$$

To determine P_i it is necessary to examine the physical processes which produce free electrons before the field is applied and determine the lifetime of these electrons in the test gap. These are examined in detail in the following sections.

C. Field Independent Sources of Free Electrons

In a test gap containing a specimen gas there are natural sources of free electrons which are independent of the applied electric field. In particular, free electrons are generated by cosmic radiation and natural radioactivity in the materials surrounding the test gap. Other

* An additional term, $-P_i P_\tau$, which will be negligibly small in cases of interest, is not included.

possible sources of free electrons independent of the electric field may be considered, such as thermal ionization of the gas or thermionic emission from the electrodes; but these all may be shown to contribute negligibly to the production of free electrons. Such sources as ultraviolet light or artificial sources of radioactivity are not considered since these are controllable experimentally and can be eliminated. This section will deal with those electrons produced by cosmic rays and natural radioactivity.

If the specimen volume of gas is shielded against radiation, cosmic radiation and natural radioactivity in material surrounding the gas contribute equally to ionization in a specimen gas, about 2 ion pair/cm^3 sec for each, or a total of 4 ion pair/cm^3 sec.[3] This figure itself does not provide the information needed to quantitatively discuss the effect of cosmic radiation and natural radioactivity on the breakdown characteristics of a pulsed gap. It is more significant to speak about the number of ionizing events which occur per second in the test volume. The flux of natural radiation is about 0.04 particles/sec - cm^2. Particle energies due to cosmic rays are in the high Mev to Bev region. Particles due to natural radioactivity are in the Mev region. In either case the specific ionization is about the same, i.e., about 70 ion pairs/cm. Thus, ionizing particles from natural sources produce bursts of electrons in the specimen gas. The number of bursts per second and the number of electrons per burst depend on test cell geometry.

D. Free Electron Lifetime

If a single free electron is in the gas volume when a voltage pulse much greater than the static breakdown voltage is applied, it will initiate a discharge. Free electrons may be present in the gap and initiate breakdown after a cosmic ray or natural radioactive event if a voltage

pulse is applied in a time shorter than the lifetime of free electrons produced by these events. It is the purpose of this section to determine the electron lifetime after such events.

Free electron decay times are determined by the diffusion rate of electrons to the container walls or electrodes in the gap, by recombination with positive ions in the volume of the gas and at the walls and electrodes, and by attachment to electronegative atoms and molecules. Gould and Roberts[4] have shown that diffusion can be neglected if either of two conditions are fulfilled,

$$pd > 25 \text{ mm Hg - cm}$$

$$\tau < 3 \times 10^{-6} d \text{ sec}$$

where p is the pressure in mm Hg, d is the gap width in centimeters, and τ is the pulse length. At atmospheric pressure and centimeter gap widths, of interest here, the first relation is easily satisfied; and diffusion may be neglected with respect to attachment. For electron densities of $10^{13} cm^{-3}$ or less, recombination may be neglected with respect to attachment. The effect of naturally occuring ionizing rays on the discharge initiation depends, therefore, on the rate of attachment of the free electrons to gas molecules. The case of air at atmospheric pressure will be considered here in detail.

Assume that an average number of electrons, n_o, are produced per ionizing ray. For an S-band guide typical path lengths would be about 3 cms, corresponding to about 200 electrons per burst. Most of these ave energies in the kilovolt region. Initially no attachment will occur, in a short time (nanoseconds) the whole group of electrons will experi- leastic and inelastic collisions which degrade the electron energy.

It is only when the energy of the electron is reduced to about 2.5 ev that oxygen attachment (the only important attachment process in air) becomes significant.

In the Appendix the decay characteristics of the free electron population are calculated from collision and attachment data. The results are shown in Figure 1. Very few electrons are lost until the electron energy approaches 2.5 ev. At 2.5 ev O_2 attachment becomes important and the electron decay begins. When the electron energy reaches 0.025 ev (thermal), the decay is exponential with a decay constant of 2×10^{-8} sec.

For an individual electron the lifetime is quite complex. It will almost certainly survive during the 1.5×10^{-9} sec required to reach 2.5 ev. The probability of attachment will then increase, particularly as the energy approaches thermal energy. The probability is about 0.4 that it will be thermalized, and this will occur at about 3×10^{-9} sec after it has been generated. If it is thermalized, it will survive about another 2×10^{-8} sec. Thus, assigning an average lifetime of 2×10^{-8} sec to an individual electron appears reasonable. This figure differs considerably from published data[5] which is obtained from afterglow measurements and which applies to decays of densities from 10^{13} electrons/cm^3 to about 10^7 electrons/cm^3.

Since electrons are generated in relatively large numbers, consideration of the lifetime of an individual electron is not of direct importance from the point of view of discharge initiation. It is the total time during which one or more electrons are available to initiate a discharge which is significant. To determine this time, effective use may be made of Figure 1. A typical track in a wave guide will produce about 200 electrons. Figure 1 shows that 80 of these will survive after 3×10^{-9} sec and be thermalized. The time for these 80 to decay to 1 is given by Equation (8A) (exponential tail in Figure 1) as follows:

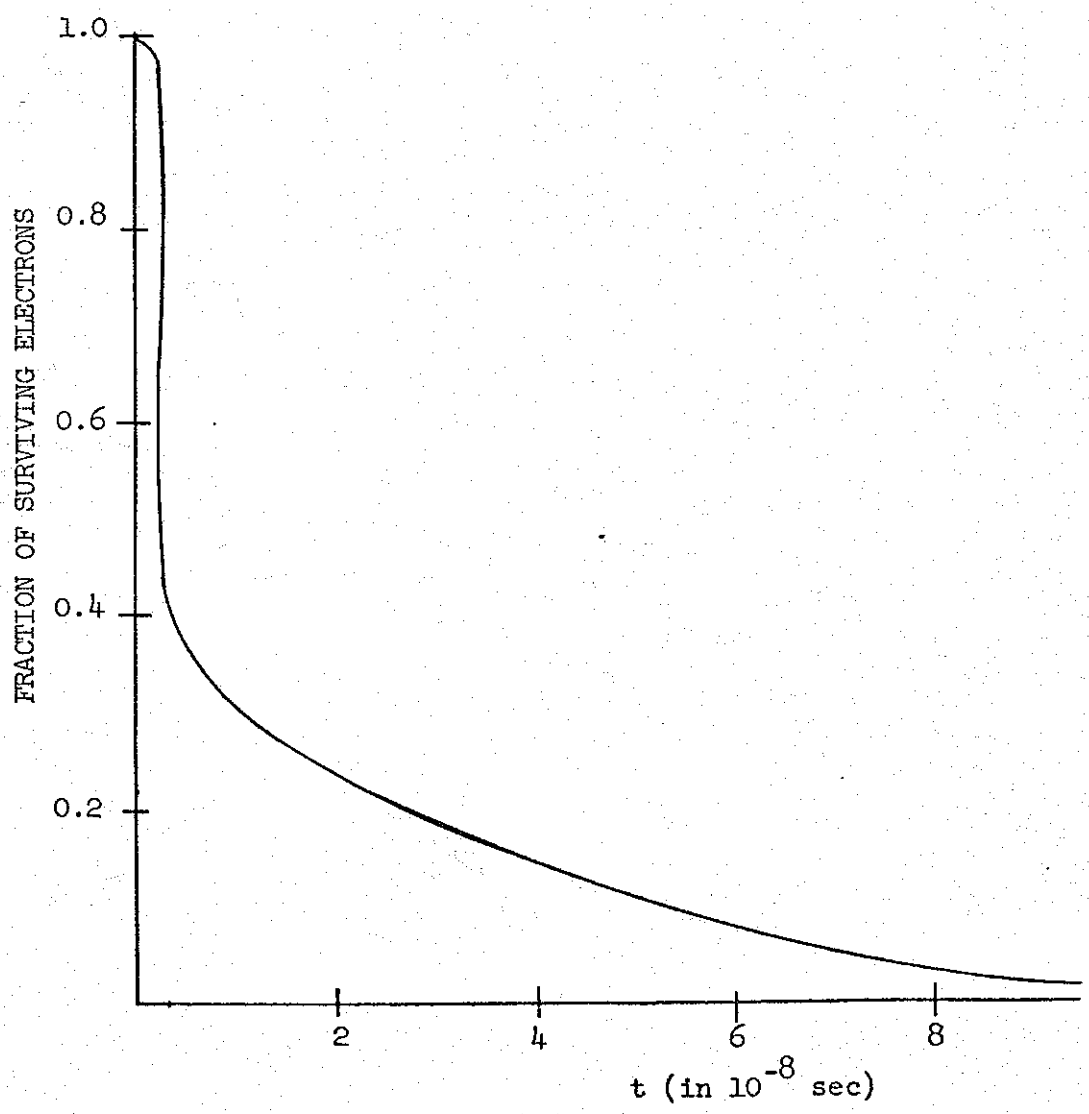

FIGURE 1. DECAY OF ELECTRON BURST

$$t = 2 \times 10^{-8} \ln 80$$
$$= 8.8 \times 10^{-8} \text{ sec}$$

Thus, adding to this time the time to reach thermal energy levels gives a total time to reduce the original number from 200 to a single electron as,

$$t_T = 9.1 \times 10^{-8} \text{ sec}$$

If a voltage in excess of breakdown is applied to the gap within 9.1×10^{-8} sec after the passage of an ionizing particle, electrons will be immediately available to initiate a discharge. Thus the effective lifetime of the burst is $\sim 10^{-7}$ sec.

E. Probability of Immediate Breakdown

If ionizing radiation produces electron bursts in the volume of the specimen gas within 9.1×10^{-8} sec of the application of the pulses, breakdown initiates immediately upon the application of the pulse. To

determine the probability that this will occur, use is made of the Poisson Distribution. This is given by,

$$P_x = \frac{m^x}{x} e^{-m} \qquad (8)$$

where P_x is the probability of observing x ionizing events in one trial and m is the mean number of ionizing events which occur in the gas volume within 9.1×10^{-8} sec of the application of the pulse. For the case of breakdown in waveguides we may take x as unity and determine m from the geometry of the test cell and measured levels of local natural ionization. Using these values, Equation (8) may be used for P_i in Equation (7) to get the total probability of breakdown per pulse as follows:

$$P_T = me^{-m} + (1 - e^{-I\tau}) \qquad (9)$$

Consider a case where only cosmic radiation and natural radioactivity are considered as sources of free electrons. If the cross sectional area of the test region is 100 cm^2, then the following values of I and m apply:

$$I = 0.04 \times 100 = 4$$

$$m = 9.1 \times 10^{-8} \times 4 = 3.6 \times 10^{-7}$$

For a 3 nanosecond pulse width Equation (8) yields,

$$P_T = 3.6 \times 10^{-7}\, e^{-3.6 \times 10^{-7}} + (1 - e^{-4 \times 3 \times 10^{-9}})$$

$$\cong 3.6 \times 10^{-7} + 1.2 \times 10^{-8}$$

The calculated probability of breakdown based on these assumptions is thus very small. It is interesting to note that it is P_i, which depends on the lifetime of electron bursts generated before the application of the pulses, which predominates. However, only cosmic radiation and natural radioactivity are considered as sources of free electrons in calculating I. This assumption is valid only at breakdown threshhold. In the presence of high electric fields I will be much greater and will depend upon the value of the electric field. This is discussed in detail in the following section.

F. Field-Assisted Free Electron Generation

In the preceding section it was shown that the probability of breakdown due to cosmic radiation and natural radioactivity is relatively small and only rarely does an ionizing event occur immediate preceding or during the pulse and initiate a discharge. If

cosmic radiation and natural radioactivity were the only source of free electrons in the discharge volume, one could speculate on the high probability of transmitting super-power microwave pulses without breakdown occuring and devising special techniques to deal with the rare breakdown event which may occur. Unfortunately, in the case of super-power pulses, the free electrons which initiate discharge do not arise from cosmic radiation or natural radioactivity but are emitted from the electrode or wave-guide wall assisted by the high local electrical field.

In the past microwave studies have dealt exclusively with the formative time for the discharge breakdown and the magnitude of that breakdown field. The statistical time lags were eliminated as an experimental inconvenience by irradiating the gap with natural radioactivity or ultraviolet light. It now appears that the statistics of initiation and underlying physical processes may be of great importance in studies of super-power microwave systems. Except for some modification necessary to take into account the time variation of the electric field, the initiation statistics and processes in the microwave case should be similar to those of the DC case. This section will therefore deal with field-assisted free electron generation in DC fields.

Various work in the study of field-assisted electron emission from electrodes was conducted by F. Llewellyn Jones[6]. He studied statistical time lags in cases where the electrode spacing was extremely small(about 0.3 millimeters). With the close spacing used, it was easy to achieve field intensities of 5×10^4 v/cm and greater. For these values of the

applied electric field, the observed statistical time lags were far too short to be explained by cosmic radiation and local radioactivity. Further work by Jones showed that there was electron emission from the cathode surface of the discharge gap which provided the discharge-initiating electrons.

1. Techniques of Jones

The method employed by Llewellyn Jones consisted of examination of the distribution of the time interval which elapsed between the application of a constant electric field well in excess of the minimum required for breakdown and the appearance of an electron emitted from the cathode. In the presence of the high field the appearance of an electron in the gap from any cause at once led to the electrical breakdown in the gap which was recorded electronically. The associated circuits limited the charge passed, at breakdown, to less than 10^{-6} coul. and also isolated the gap from the source of potential within a time of 10^{-6} sec. Under these conditions the electrode surface was not significantly altered during the measurements.

Jones used a triggered oscilloscope to record statistical time lags. Application of the pulse triggered a calibrated time base, and breakdown blanked the trace. The system ran repetitively, and traces were recorded on a vertical moving photographic film. A typical record of time lags was a series of time base traces of varying lengths (time lags), each trace starting at the application of a trial pulse and terminated (blanked) when discharge occurred.

FOREWORD

Gaseous breakdown can impose serious limitations on the capabilities of high-power microwave transmitting systems. Although much is known of this phenomenon for DC and microwave pulse systems, considerably more detailed theoretical and experimental information is needed to advance the state-of-the-art in high-power microwave transmitting systems.

Technical considerations indicated that improved performance may be realized by using reduced pulse widths. Rome Air Development Center is conducting an intensive theoretical and experimental study of breakdown phenomenon in the nanosecond region. BDM has conducted theoretical investigations under this program. An earlier report presented the results of the first six months of BDM activity. During the second six month period BDM investigated the processes of discharge initiation and the feasibility of photometric techniques for studying discharge characteristics in the nanosecond region. The results of this study are presented in this report.

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Since the surface emission of electrons is statistical, the surface current I is related to the time by Equation (4) given here again as follows:

$$\frac{n}{n_o} = e^{-It}$$

The electron emission, I, may thus be obtained either from the slope of ln n plotted versus t or by calculating the average time for breakdown, that is the average statistical time, $\bar{t}$. The average statistical time can be shown to be

$$\bar{t} = \frac{1}{I}$$

2. Influence of Micro-Geometry and Nature of the Surface

Direct measurement of the rate of electron emission from different surfaces gives the following results:

Pre-breakdown electron emission from clean, smooth, cold cathodes of ordinary metals under applied electric fields of the order of 10^4 v/cm is very small. However, the presence of microscopic irregularities on the cathode surface enhance locally the applied electric field and increases the local emission. This locally enhanced field is the field effective in extracting electrons from the surface and not the macroscopic applied field. The presence of a layer of very fine dust or of a layer of oxide produces very much the same effect, causing enhanced emission at moderate field strengths.

Average values for the emission current from different metal surfaces in various conditions of surface finish are given in Table 1. The results were obtained at the same value of the macroscopic electric field E_n (equal to 5×10^4 v/cm).

TABLE I

The Influence of Surface Conditions and Nature of Metal on the Electron Emission in Air

Metal Surface	Electrons emitted per second under applied field 5×10^4 volts/cm from Nickel	Brass	Steel	Molybdenum
Freshly turned	18×10^3	8×10^5	90×10^3	30×10^3
Tarnish oxide layer	8×10^3	5×10^5	30×10^3	7×10^3
Highly polished	6×10^3	10^5	5×10^3	2×10^3

Metal surfaces are least active when they are clean and have been carefully polished. The same surfaces after exposure to the atmosphere for a period of hours show a definite increase in emission which can be as much as an order of magnitude or greater. Also, it appears that it is the actual state of the metal surface, rather than the metal itself, that governs the activity, at least for metals of roughly the same physical properties.

3. The Dependence of the Emission on the Applied Electric Fields

Llewellyn Jones established that there is a general correlation between the applied electric fields and the measured electron emission current. An example of this field dependence is given in Figure 2 for molybdenum and nickel surfaces in air. Over the limited range of measurement shown in Figure 2 the emission current is given closely by the expression for cold field emission developed by Fowler and Nordheim[7].

$$I = \left[38.5 \times 10^{12} \zeta^{\frac{1}{2}} F^2 S/(\Phi + \zeta)\Phi^{\frac{1}{2}}\right] \exp\left(-6.8 \times 10^7 \Phi^{3/2}/F\right) \quad (10)$$

where

I is the number of electrons emitted per second from a surface of area S

φ is the work function

ζ the fermi energy in electron volts

and

$$F = NE$$

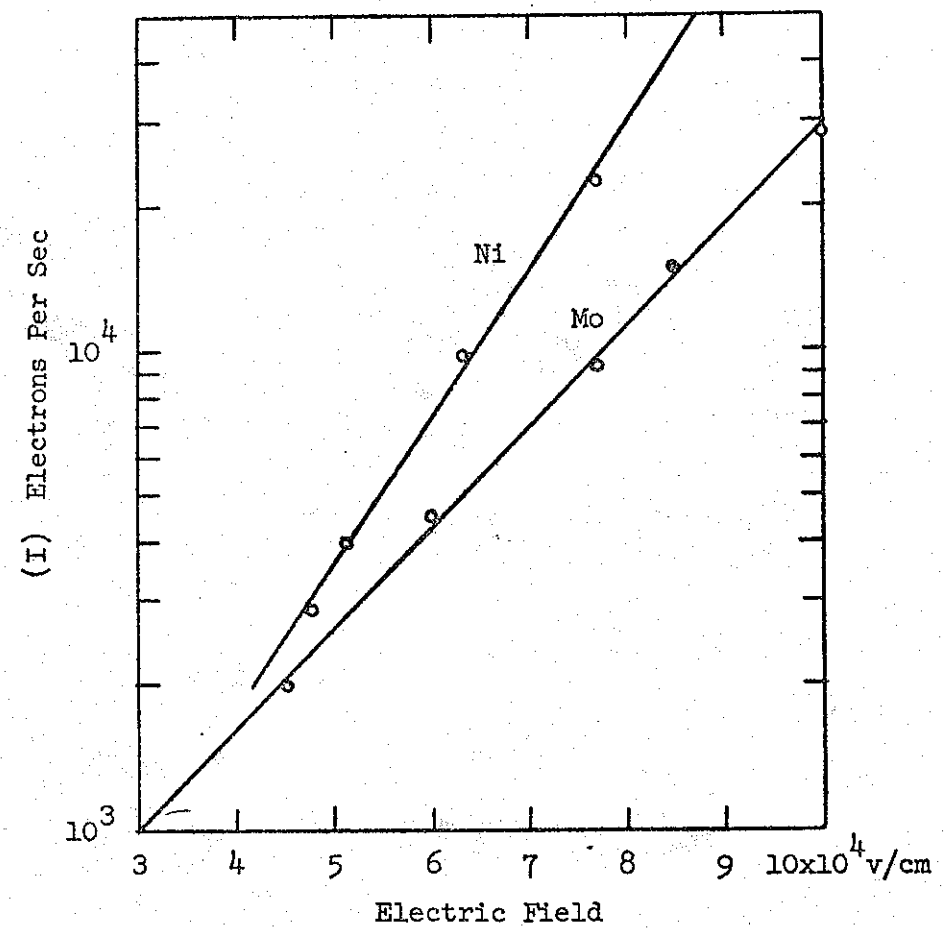

FIGURE 2. VARIATION OF CURRENT WITH ELECTRIC FIELD FOR NICKEL & MOLYBDENUM

where

F microscopic field at the cathode surface

N is a factor representing the local intensification of the macroscopic field E by microscopic roughness

Two conditions of oxidized layers are differentiated by Llewellyn Jones: thick oxidized layers (greater than approximately 10^{-5}cm), as commonly found on metals exposed to the atmosphere, and thin oxidized layers (approximately 10^{-7}cm).

In the case of thick oxidized layers substantial emission of 10^4 to 10^5 electrons/s is obtained from cathodes of nickel and tungsten with electric fields of about 10^5 v/cm. By relating this emission to the electric field by a Fowler-Nordheim equation, estimates of the work function and emitting area of the source of the electrons were made. It was found that the effective work function for the emitting source on oxidized nickel and tungsten was roughly 0.5 e.v. and that the emitting areas were 10^{-13} cm^2. This is consistent with the view that the electrons were obtained from the oxide itself and not from the underlying metals. Presence of tarnished films and oxides on electrodes inhance the cold emission greatly and play an important part in electron production.

The results for thin tarnished films are consistant with the view that electrons emitted are extracted from the metal substrate by the high electric field set up across the thin surface film when covered with a layer of positive ions, the presence of positive ions on the thin film being essential to the emission mechanism which follows a field law; this high emission does not occur when the thin surface tarnished film is absent.

Very recent studies by Little and Whitney[8] seem to support the Fowler-Nordheim theory of cold field emission and show that it can also be caused by sharp surface irregularities which greatly enhance electric fields. Using a shadow electron microscope, projections about 2μ high were found at pre-breakdown electron emission sites. The calculation by Lewis[9] showed that a prolate hemispheroid on a flat surface with a height to base diameter ratio of 8 produces a field enhancement, M, of 100. This means at the whisker, or projection, the electric field would be 10^7 v/cm if the gross field were only 10^5 v/cm. Little & Whitney shows that this pre-breakdown emission is independent of emitter temperature up to 1000°K.

On the other hand, the emission curve shown in Figure 2 may also be satisfied by the field assisted thermionic equation by Schottky[10]

$$I = I_o \exp (e^{3/2}E^{1/2}/kT) \qquad (11)$$

where e is the electronic charge, E is the field strength and

$$I_o = AT^2 \exp (-\Phi/kT) \qquad (12)$$

is the electron emission at zero electric field at a temperature T and φ is the work function of the solid. This approach is given some support by the work of Lewis[9].

The range of electric field values for which measurements have been made is small; and, considerably extended range measurements must be made to determine which field expression, if either, is the accurate one.

4. Conditioning

In almost all cases the condition of the surface contributes importantly to the character of the emission. Of very special interest in the approach to super-power microwave transmission is the work by Llewellyn-Jones in which he was able to "condition" electrodes to eliminate surface emission. This required a special sparking procedure.

The conditioning process consists of prolonged bombardment of oxide - covered surfaces by positive ions in a low, current-limited, hydrogen glow discharge. This ion bombardment was alternated with heat treatments in vacuum to remove gas atoms driven into the metal by the discharge. When this process was repeated at voltages approximately twice the static breakdown voltage, at hydrogen pressures of 600 mm of Hg, the electron emission was reduced to a level accounted for by cosmic rays and natural radioactivity.

In the case of iron this process must be repeated many times over a period of many hours. On the other hand, a highly polished nickel cathode requires only 15 minutes of square pulses at a rate of 50 a second to condition the surface. The nickel emission is initially 10^6 electrons/seconds; and after 15 minutes, it is less than 100 electrons/second.

II. OPTICAL METHOD

A. Introduction

In detecting the initiation and the build-up of breakdown currents in an avalanche, it is desireable to measure the discharge current early in the exponential build-up. In cases where the microwave technique is used, the reflection is only strong in the region of the critical electron density ($>10^{11}$ electrons/cm^3, e.g., at S-Band). With modern nanosecond pulse measuring equipment, measurements of anode current provide about the same sensitivity and resolution.

The feasibility of using optical diagnostic techniques in discharge growth investigations was considered during the first six-month period under this contract. It was shown that during the discharge build-up the power absorbed, P_v, in the gas during discharge build-up was given by,

$$P_v = ev_d En_o \exp(\nu_{net} t) \qquad (13)$$

where

- e - electronic charge
- v_d - electron velocity in the applied electric field
- E - applied electric field
- n_o - initial electron density in electrons/cm^3
- ν_{net} - ionization coefficient
- t - time

Preliminary calculations of the light output were made, based on a conversion efficiency figure of 10^{-5}. These indicated that optical observations of discharge growth were possible.

During the second six-month effort under this program, the problem of more accurate calculation of the conversion efficiency from electrical power absorbed in the gas to light power out was examined in detail. This section presents the results.

B. Electric-to-Optical Power Conversion Efficiency

Although measurements have been made of the light output efficiency of gas discharge devices, the information which is available applies to cases of low pressure (few mm of Hg). The case under consideration in this program is atmospheric pressure, and quantitative information on the efficiency of conversion from electrical to optical power is not available. It is expected that the conversion efficiency will be considerably less at higher pressures than it is for the low pressures. In the high pressure case account must be taken of the non-radiative loss of excited states due to collisions with neutral molecules.

It is possible to develop a relationship between the efficiencies of the high pressure and low pressure cases. To do this, it is necessary to assume that the ratio E/p is the same in each case and, therefore, the dynamics of electron collisions are identical. Since we are considering the breakdown levels of 40,000 v/cm at 760 mm Hg, the associated low pressure case corresponds to a few hundred v/cm at several mm pressure.

For either the high or low pressure case, where the E/p ratio is the same, the rate of formation of excited states by a single electron is also the same. In equilibrium this rate is equal to the rate of loss by radiation and by non-radiative collisions. This is given by the following:

$$\frac{dn}{dt} = An + Cn \tag{14}$$

Here A and C are the transition probabilities for radiative and non-radiative transitions respectively. The fraction, f, of all excited states which decay radiatively is then given by,

$$f = \frac{A}{A + C} = \frac{1}{1 + \frac{C}{A}} \tag{15}$$

It may be shown that A is the reciprocal lifetime ($A = \frac{1}{\tau_r}$) of the excited state in the low pressure or vacuum case. This is of the order of 10^{-8} seconds. On the other hand, C is the non-radiative transition rate. It is only during a collision with a gas molecule that a non-radiative transition can occur. The energy of the excited state is transferred as kinetic energy to the colliding molecules. This is the so-called collision of the second kind, or non-elastic collision. Accordingly, we may represent C as follows:*

$$C = 5 \times 10^9 k \frac{p}{p_o} \text{ sec}^{-1}$$

where

k - a constant ≤ 1

p - pressure

p_o - atmospheric pressure

*Note: Taking the collision frequency at p_o as equal to 5×10^9 sec^{-1}.

From this expression it is seen that there is an upper limit on the value of C. This is the case where k equals 1, and corresponds to a situation in which each collision experienced by the excited state results in a non-radiative transition. Thus, we may rewrite Equation (15) as the following inequality:

$$f \geq \frac{1}{1 + 5 \times 10^{9} \frac{P}{P_o} \tau_r} \qquad (16)$$

Taking this expression, we may now consider values for the low pressure and high pressure cases as follows:

Low Pressure Case:

For this case the assumed parameters are:

P - 1 mm Hg

P_o - 760 mm Hg

τ_r - 10^{-8}

$$f \geq \frac{1}{1 + 6.5 \times 10^{-2}} \cong 1$$

High Pressure Case:

For this case the assumed parameters are:

$P = P_o$

$\tau_r = 10^{-8}$

$$f \geq \frac{1}{1 + 50} \cong 0.02$$

which yields an abosolute electric-to-optical power conversion efficiency of 2×10^{-4} for the high pressure case, assuming 1% electric-to-optical power conversion efficiency at low pressure.[11] This is ten times the efficiency

necessary to measure light output with a nanosecond resolution as shown in the first six-month report.

C. Temporal Observation

The temporal growth of the discharge in either the microwave or DC case can be treated in some detail theoretically. Microwave breakdown is discussed by Gould and Roberts[4], and the results of their theoretical considerations are confirmed by experiments using a microwave resonance cavity. Similar work for the formative time lag and the DC case was done by Fletcher[12] in 1949. Recently, Proud and Felsenthal[13] have used Fletcher's DC technique with pulses of widths of 4 and 8 ns to extend the results of Gould and Roberts .

In the experimental studies of discharge growth, measurements are made of the current flow to the electrodes (DC case) or of the reflected energy in the microwave case. It has been shown that the light output power from the discharge region will permit unusually sensitive measurements of the early phases of discharge growth, using gas fluorescence as the diagnostic tool. Using a photomultiplier and a high speed oscilloscope, such as the Tectronix 519, it would be possible to record the discharge growth by detecting the gas fluoresence with 1 ns resolution. The method would be capable of recording discharge current levels of 1.0 microampere, and this would permit observation of the earliest phases of discharge which are not accessible to the electrode current or microwave reflection techniques.

For the high pressure case the early phases of discharge are quite similar in both the microwave and DC cases. Both may be described by the

so-called Diffusion Equation which relates electron production by ionization and electron loss by attachment and diffusion. This equation is as follows:

$$\frac{\partial n}{\partial t} = (\nu_i - \nu_a)n - \nabla^2 Dn$$

where n is the electron density, ν_i and ν_a are the ionization and attachment coefficients, and D is the diffusion constant. Gould and Roberts[4] show that in the microwave case at high pressures, the diffusion loss is negligible and the temporal growth of the discharge is given by,

$$\ln \frac{n}{n_o} = < \nu_i - \nu_a > t$$

where n_o is the initial electron density and $< \nu_i - \nu_a >$ is the average value of $\nu_i - \nu_a$ over a complete cycle of RF. For the case of a short video pulse or the early stages of DC breakdown in which the electrode effects have not entered, it may be shown that diffusion is negligible; and the growth equation is given by,

$$\ln \frac{n}{n_o} = (\nu_i - \nu_a)\, t$$

where the values assigned ν_i and ν_a are the DC values.

It is readily seen by comparing the two growth equations that they differ only in the use of average values in the microwave case and DC values for the video case. The correspondence between the video breakdown and microwave breakdown cases are discussed in some detail by Proud and Felsenthal.[13]

D. Spatial Observation

Optical observation is spatially selective in that it allows a predetermined volume to be studied. The size of the volume may be determined by selecting the focal length of the light gathering lens and using an aperture stop to determine the depth of field. The location of the volume in the test gap may be selected with a field of view limiting aperture as shown in Figure 3.

Spatial separation of the electron initiating events makes it possible to study free-space breakdown far from electrode surfaces. The electrodes may have a dominating influence on breakdown formation rates. Previous studies of avalanche growth have been conducted with closely spaced electrodes.

In the case of expansion chamber methods the introduction of contaminants are necessary to indicate the charge presence which could affect both initiation and growth rates. Optical methods are remote as well as spatially selective and, hence, will not affect the physical case to be studied.

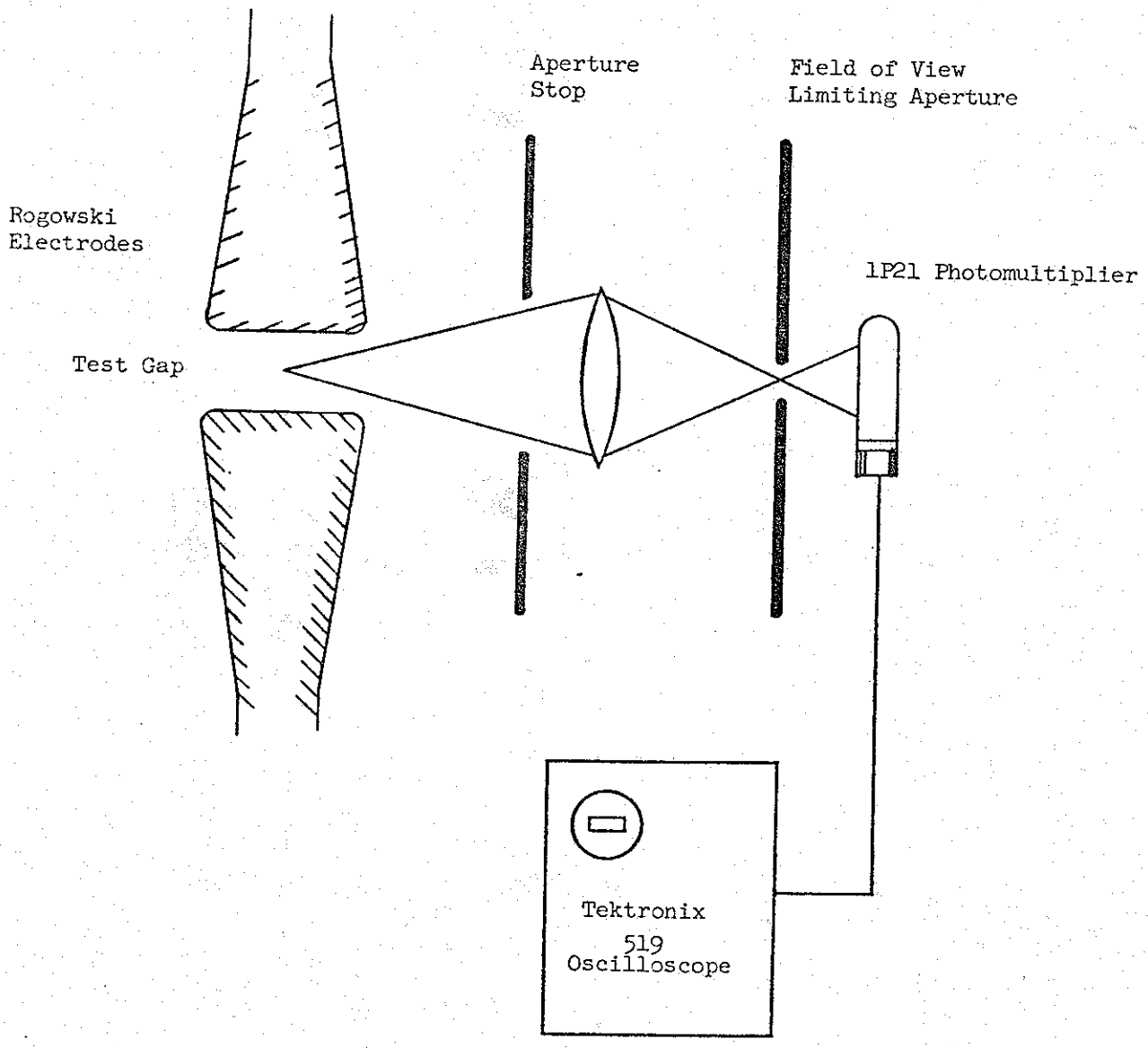

FIGURE 3. TEST GAP & OPTICAL RECORDING SYSTEM

III. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. Field-assisted electron emission from electrode or wave guide walls is the major agency of discharge initiation in the high-field DC or microwave cases.

2. A further understanding of the statistics and underlying physical processes of field-assisted emission is essential to the development of design techniques which minimize breakdown in superpower microwave systems.

3. An optical emission technique is feasible and required to observe the early temporal and spatial distribution of breakdown.

B. Recommendations

1. Further study of the effects of surface characteristics on field-assisted electron emission.

2. Study of the effects of surface conditioning on field-assisted electron emission.

3. Investigation of dependence of field-assisted electron emission on field strength. A wide range of field strengths should be used.

4. Development of the optical emission techniques for the study of discharge temporal and spatial growth.

5. Development of a free space statistical breakdown model to determine the reflection characteristics of free space in which discharges are initiated randomly in space and time by cosmic rays and natural radioactivity during the passage of a high-power pulse.

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APPENDIX

Electron Energy Decay Time

The time required for the electron energy to decay from kev to thermal energies may be calculated from the average fraction of energy lost, λ, by an electron in a collision with a molecule. In a molecular gas such as air, inelastic collisions excite vibrational and rotational states such that λ is a function of energy. Taking u as the energy of the electron in e.v., the energy loss per collision is,

$$\frac{-du}{u} = \lambda \tag{1A}$$

If there are ν_c collisions per second, the rate of energy loss is,

$$\frac{du}{dt} = -\lambda \nu_c u \tag{2A}$$

But ν_c is related to the electron energy as follows:

$$\nu_c = 2.46 \times 10^{12} u^{1/2} \tag{3A}$$

where the electron mean free path is taken as 2.5×10^{-5} cms. Combining Equations (2A) and (3A) yields,

$$\frac{-du}{u^{3/2}} = 2.46 \times 10^{12} \lambda dt \tag{4A}$$

Integrating, and noting that at $t = 0$ the electron energy is u_o, gives the expression for free electron energy as a function of time,

$$u^{-\frac{1}{2}} - u_o^{-\frac{1}{2}} = 1.23 \times 10^{12} \lambda t \qquad (5A)$$

In using Equation (5A) to calculate the time to reach 2.5 ev from kilovolt levels, the time, t, is insensitive to the selection of the initial value of the energy, u_o. It does, however, vary inversely with the selection of λ. If only elastic collisions are assumed ($\lambda = 3.7 \times 10^{-5}$), then the decay time to 2.5 ev is 1.5×10^{-8} sec. If inelastic collisions are considered (a choice for λ of 2×10^{-3} is reasonable), the decay time to 2.5 ev is 2.6×10^{-10} sec. This value is more realistic and agrees with values deduced from range vs. energy tables for electrons.

When electron energies approach 2.5 ev, O_2 attachment becomes important. This is shown in Figure (1A).[14] Since N_2 is a non-attaching gas, this O_2 attachment is the only significant attachment process. The rate of loss of electrons by attachment can be considered in two steps: a) loss rate as the energy is degraded from 2.5 ev to thermal energy, and b) the loss rate after the electrons reach thermal equilibrium with the gas (average energy 0.025 ev). For step a) the rate of loss of electrons is given by,

$$\frac{dn}{dt} = 2.46 \times 10^{12} u^{\frac{1}{2}} nh \qquad (6A)$$

where n is the number of surviving free electrons, h is the attachment frequency and u is the energy of the electron.

To find n as a function of time from Equation (6A), it is necessary to use numerical integration and values of h from Figure 1A*. To calculate finite time differences for the integration, the appropriate values for λ are given by Massey and Burhop[15]. These vary from 2×10^{-4} at 0.025 ev to 3×10^{-2} at 2.5 ev. Figure 1, which shows free electron population as a function of time, presents the results of this numerical integration in the central portion of the curve.

To get the "tail" of the curve, corresponding to the time after which the electrons are in thermal equilibrium with the gas, a different approach is required. For this case a fixed velocity of 0.025 volts and a corresponding fixed collision frequency ν_c of $3 \times 10^{11} \text{sec}^{-1}$ are used. For this case the rate of loss of electrons is given by,

$$\frac{dn}{dt} = \nu_c h n \qquad (7A)$$

Integration yields,

$$n = n_t e^{-\nu_c h t} \qquad (8A)$$

where n_t corresponds to the number that reaches thermal energies and h is the attachment coefficient appropriate to 0.025 volts. From Figure (1A)

*Note: Figure (1A) gives values for pure O_2. When used for air, these values are reduced by a factor of 5.

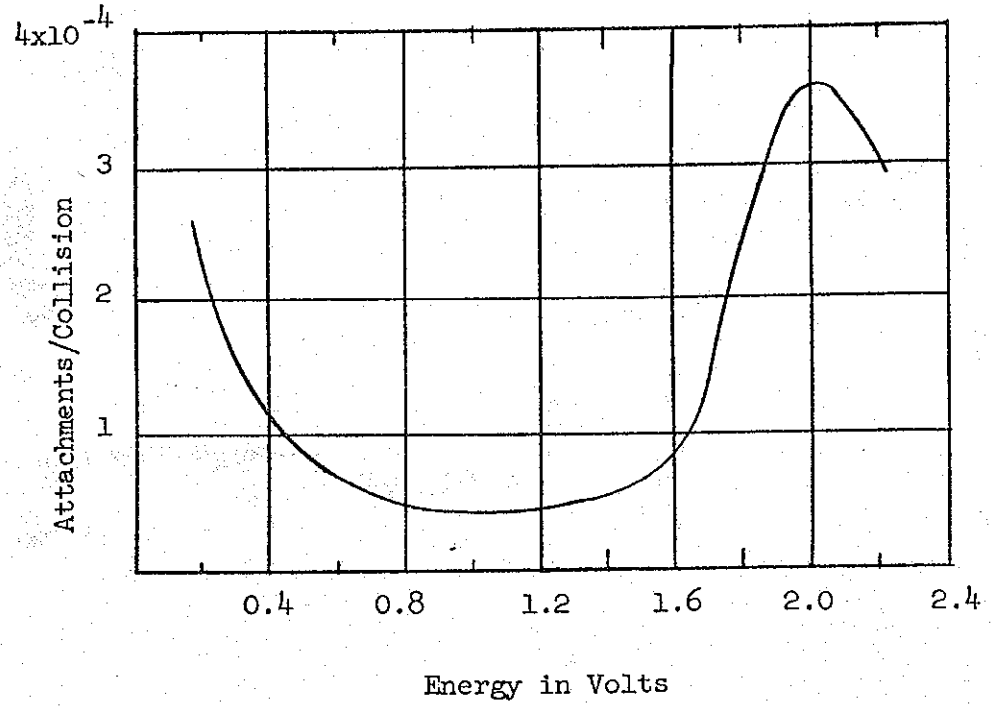

FIGURE 1A. ELECTRON ATTACHMENT COEFFICIENT AS A FUNCTION OF ENERGY IN OXYGEN

h is estimated as 1.6×10^{-4}. Thus, the decay of electron population which reaches thermal energy is exponential with a decay constant given by,

$$\frac{1}{\nu_c h} = \frac{1}{(3 \times 10^{11})\ (1.6 \times 10^{-4})}$$

$$= 2 \times 10^{-8} \text{ sec}$$